Reduced-Order Modeling Method for Fatigue Life Prediction of Hybrid Electric Vehicle Batteries

Sung-Kwon Hong, Bogdan I. Epureanu,
Matthew P. Castanier

10 August 2012

GVSETS

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **13 JUL 2012**	2. REPORT TYPE **Briefing**	3. DATES COVERED **01-06-2012 to 01-07-2012**

4. TITLE AND SUBTITLE
REDUCED-ORDER MODELING METHOD FOR FATIGUE LIFE PREDICTION OF HYBRID ELECTRIC VEHICLE BATTERIES

5a. CONTRACT NUMBER
W56H2V-04-2-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Matt Castanier; Sung-Kwon Hong; Bogdan Epureanu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Michigan,1011 N University Ave,Ann Arbor,Mi,48109

8. PERFORMING ORGANIZATION REPORT NUMBER
; #23127

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#23127

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted to 2012 NDIA Ground Vehicle Systems Engineering and Technology Symposium August 14-16 Troy, Michigan

14. ABSTRACT
briefing charts.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**10**	

Contents

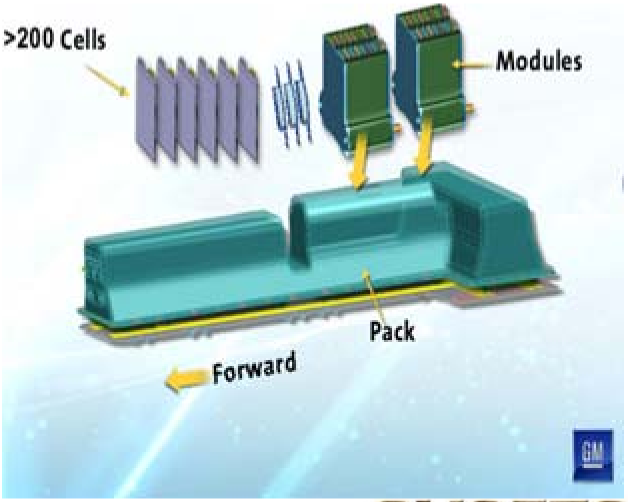
MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Objectives
- Structural Battery Model
- Parametric Reduced-Order Models (PROMs)
  - Numerical Results: Forced response of academic battery pack
    - Full-order models
    - PROMs
  - Numerical Results: Detection of highest vibrating cells
    - Three cases of variations
    - Statistical Results
- Conclusions

Objectives

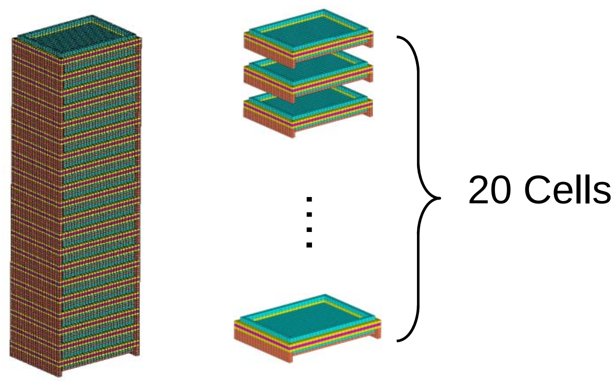
- Gain better understanding of structural dynamics featuring very high modal density
  - Special attention to hybrid electric vehicle (HEV) battery packs
  - For high modal density, small cell-to-cell structural variations have very large consequences for the dynamics of the pack
- Develop an efficient and accurate computational method for predicting the structural dynamic response of HEV batteries
- Enable fatigue life predictions by performing statistical dynamic response calculations

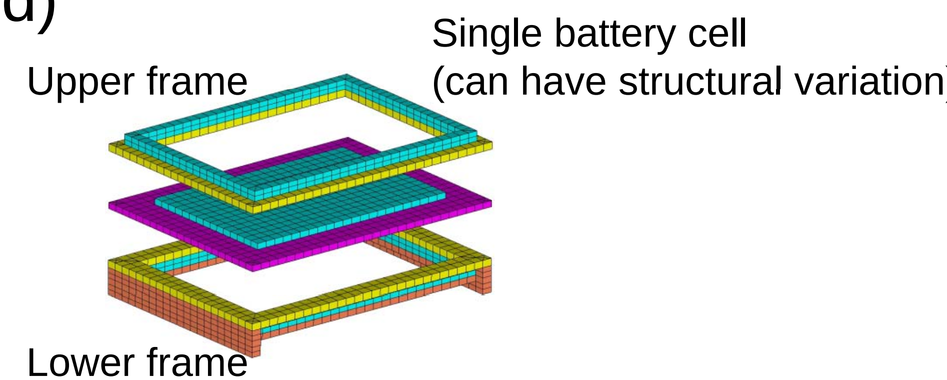
http://jcwinnie.biz/wordpress/?p=2477



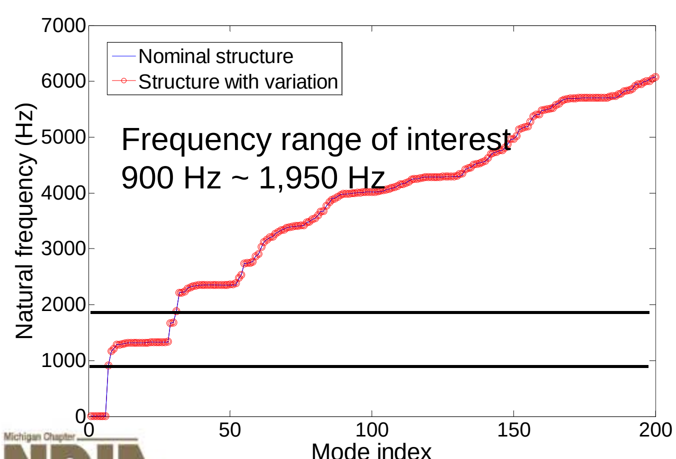
Academic Battery Model

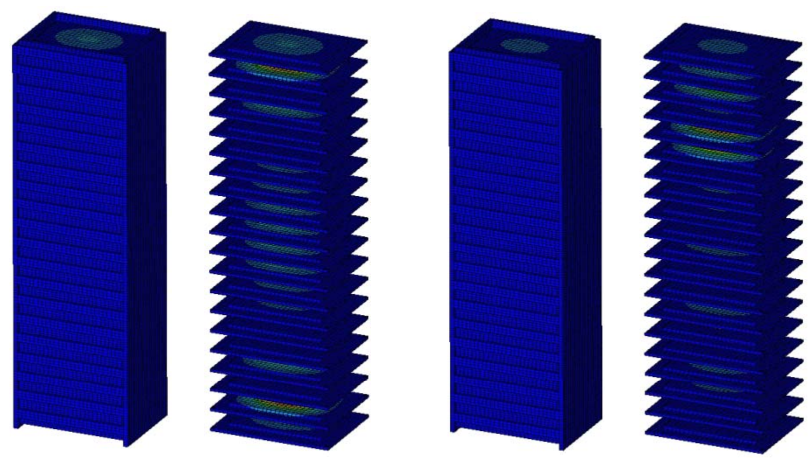
- Battery has 20 cells (stacked)





- Dynamic response (natural frequencies and mode shapes)





Nominal structure Structure with variations in cells

Mode shapes are sensitive to variations, but natural frequencies are not

Parametric Reduced-Order Models (PROMs): Key Ideas

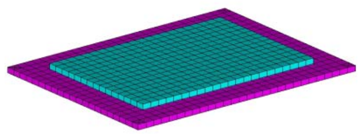
MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Modes ($\mathbf{\Phi}_M$)of a **structure with small parametric variations** and high modal density (e.g., a batter pack) can be approximated using a **linear combination of modes ($\mathbf{\Phi}_T$) of the structure with nominal parameters**

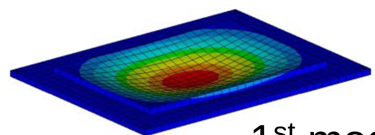
  $\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \longrightarrow \mathbf{\Phi}_T$ (Mode for nominal structure)

  $(\mathbf{M} + \mathbf{M}^{\delta})\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + (\mathbf{K} + \mathbf{K}^{\delta})\mathbf{x} = \mathbf{F} \longrightarrow \mathbf{\Phi}_M$ (Mode for structure with variations)

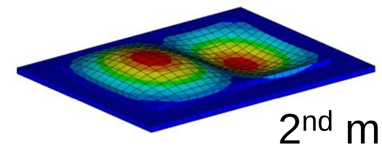
- The **motion in each of the cell**s is plate-like with fixed boundary



Single battery cell with fixed boundary (nominal)



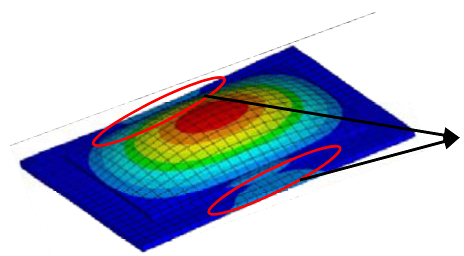
1st mode of cell



2nd mode of cell

The effects of parameter variability are captured by **cantilevered plate modes**

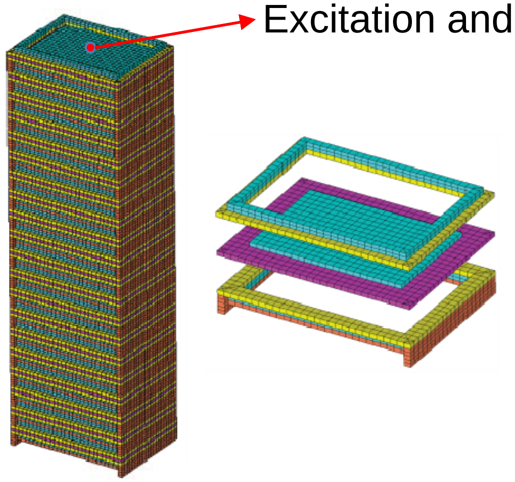
- To capture the effect of the motion of the boundary of battery pack, cantilevered plate mode with **boundary (frame) displaced as in the nominal modes** are used

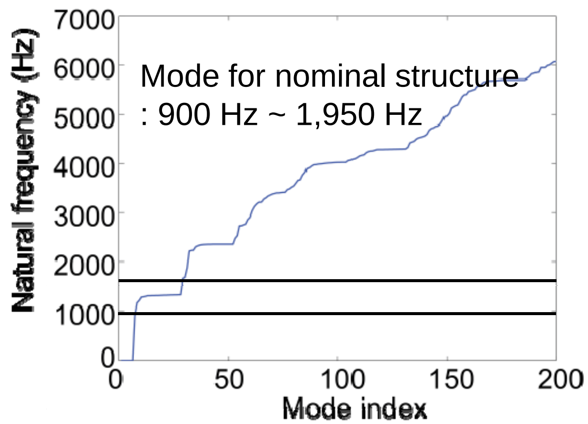


Numerical Results: Full-Order Models

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

Excitation and response point



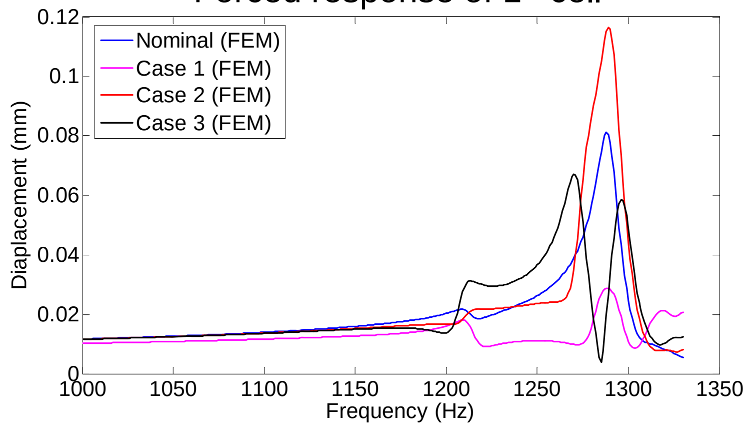


Three cases of Young's modulus variations in various cells

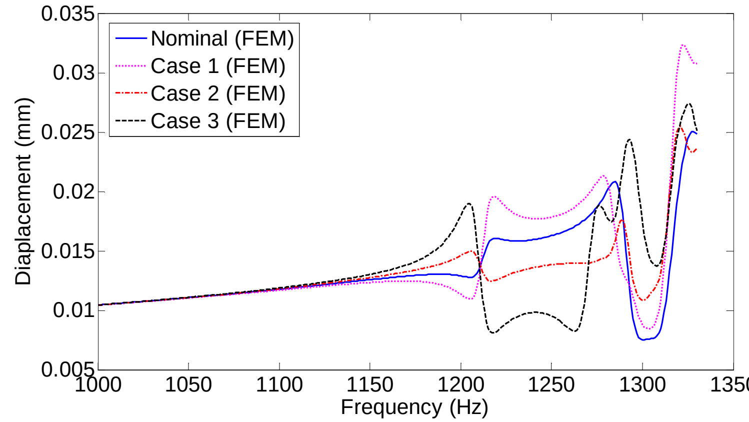
Case 1		Case 2		Case 3	
Cell	Variation	Cell	Variation	Cell	Variation
1	5%	4	10%	3	3%
5	-7%	7	-8%	9	-5%
12	1%	10	3%	13	2%
16	3%	19	-5%	20	-5%

Total DOFs: **208,752**, 20 battery cells are stacked
Material: Steel

Forced response of 1st cell



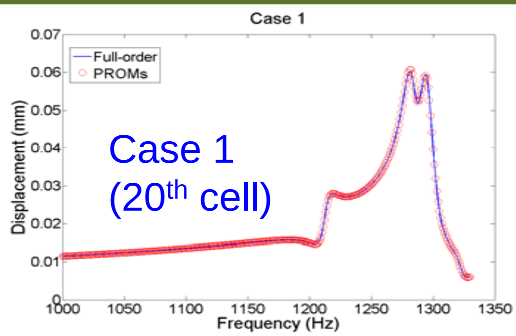
Forced response of 18th cell

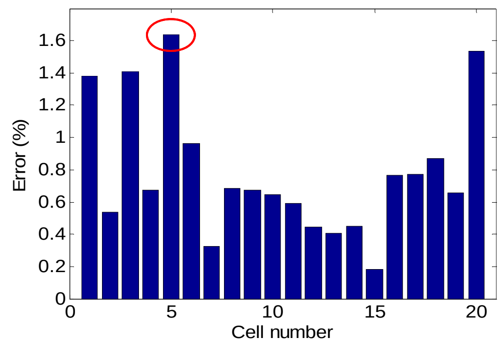


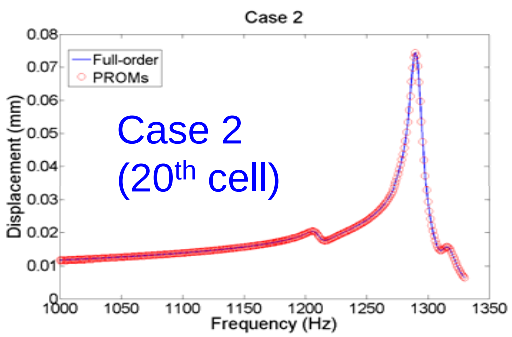
CPU time for reanalysis: 105 min 50 sec ~ 110 min 25sec (NASTRAN sol 108)

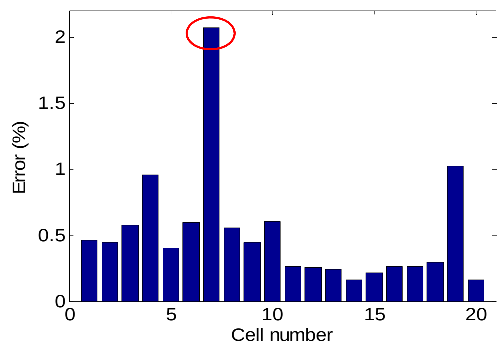
Numerical Results: PROMs

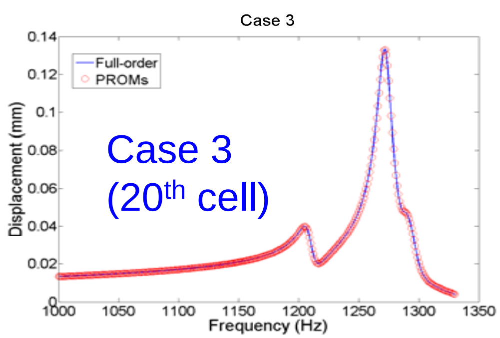
MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

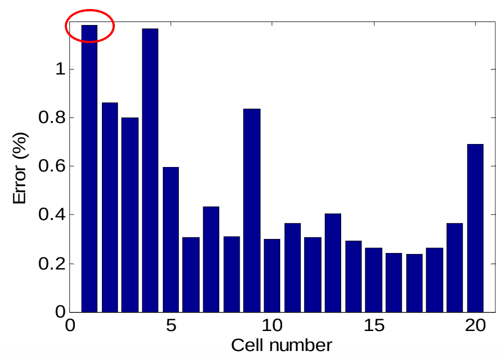












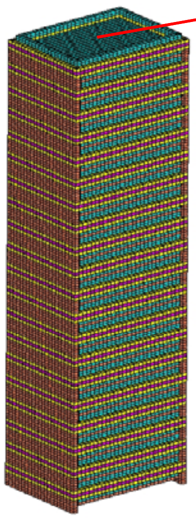
Reduced-DOFs: 25

Maximum error:
Case 1: 1.64%
Case 2: 2.07%
Case 3: 1.18%

CPU time for reanalysis:
0.71 - 0.85 sec

PROM reanalysis is **9,000 times faster** than that of full-order model

Numerical Results: Detection of Highest Vibrating Cells

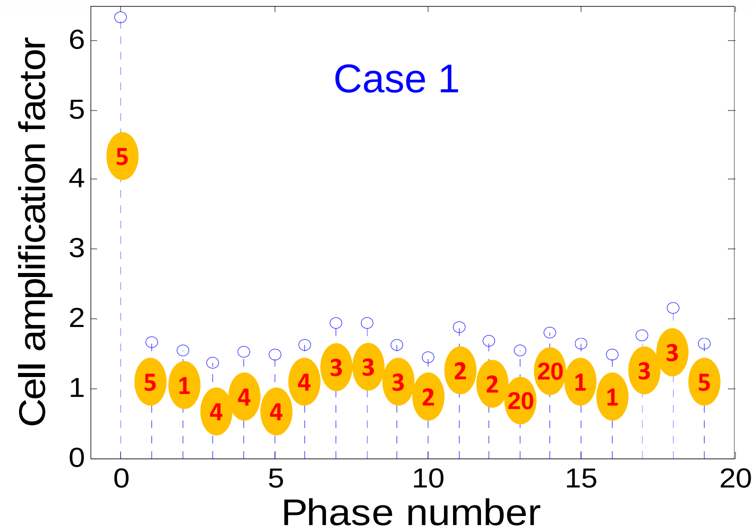


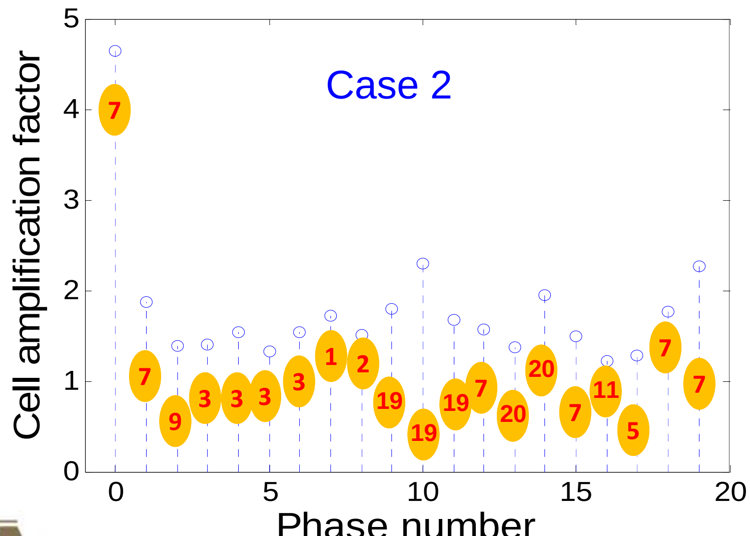
Traveling wave excitation to the center nodes of each battery cell

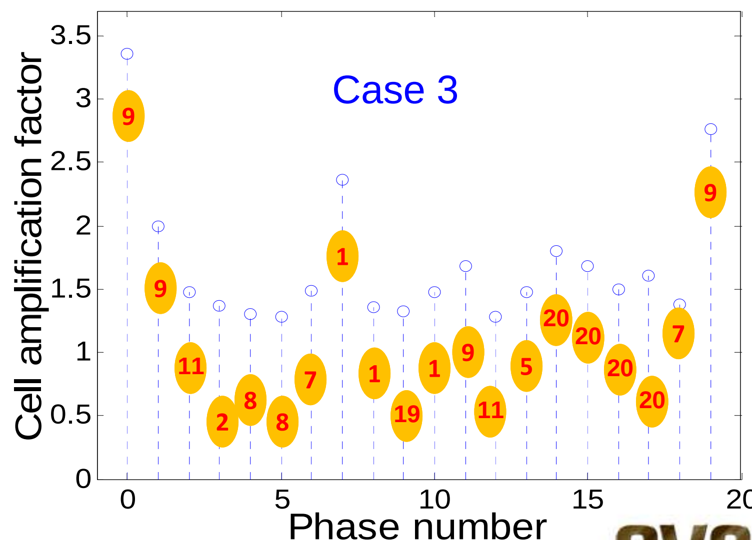
Cell amplification factor (CAF)

$$\mathrm{CAF}_k^j = \max_{i=1,\cdots,20}\left(\frac{\max_\omega(|A_i|^{\Delta p})}{\max_\omega(|A_i|^{\mathrm{Nominal}})}\right)$$

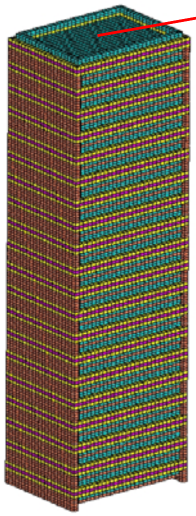
#: Highest vibrating cell for each phase







Numerical Results: Statistical Analysis



Traveling wave excitation applied to center nodes of each battery cell

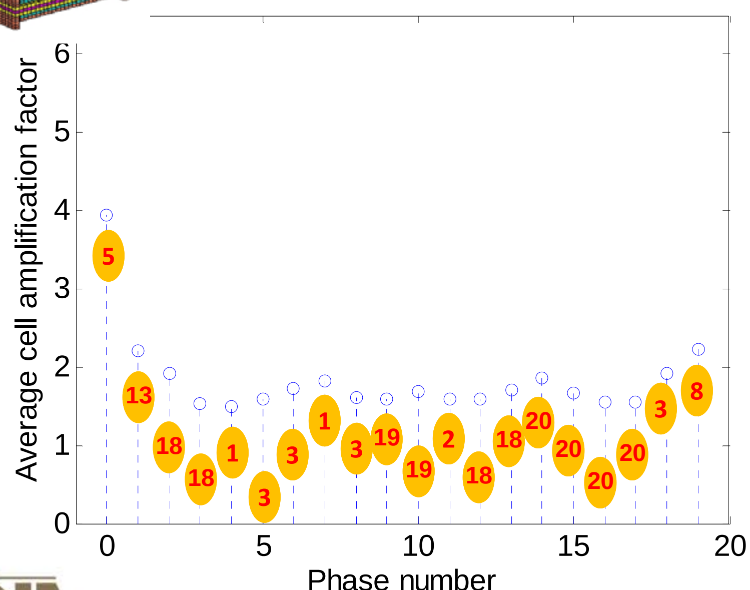
Average CAF:

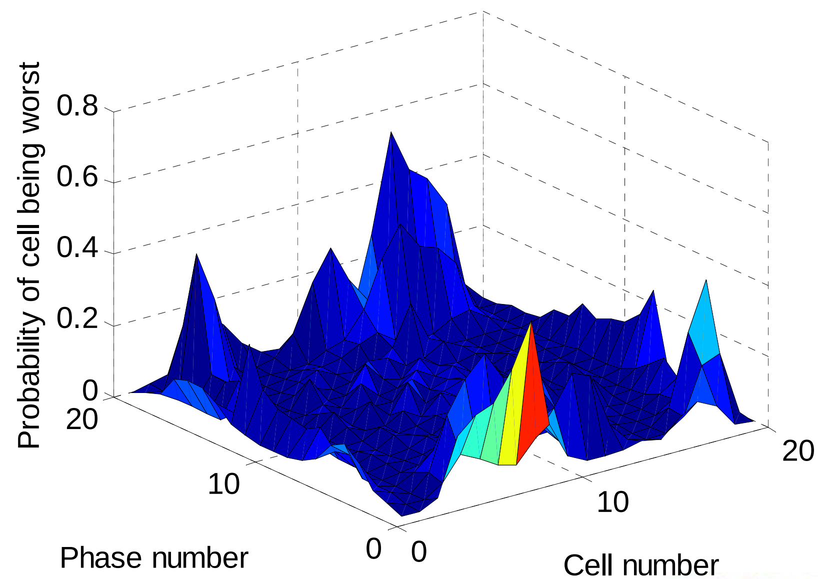
$$\mathrm{CAF}_k^j(\mathrm{AVG}) = \max_{i=1,\cdots,20}\left(\frac{1/10,000\sum_{j=1}^{10,000}\max_\omega(|A_i|^{\Delta p})}{\max_\omega(|A_i|^{\mathrm{Nominal}})}\right)$$

10,000 cases of elastic modulus variation to all 20 cells

Analysis time: 0.8 sec × 20 phases × 10,000 cases = 160,000 sec (44 hours)

#: Statistically highest vibrating cell for each phase





Conclusions

- **Introduced efficient structural dynamic simulation** capability for HEV batteries
  - Enables **fatigue life prediction**
- **Developed parametric reduced-order models** (PROMS) to capture dynamic response very quickly for structures featuring **high modal density**
  - **Reanalysis time** of new PROMs for each variation is **9,000 - 10,000 times faster** than that of full-order models
- Identified the **weakest cell (highest vibration)** by using **statistical analysis** based on cell amplification factors